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EVAPOTRANSPIRATION OF IRRIGATED WINTER WHEAT, SORGHUM, AND CORN

by

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Summary:

Evapotranspiration of winter wheat, sorghum, and corn was measured with weighing lysimeters at Bushland, TX, for the 1989-90, 1991-92, 1992-93, 1988 and 1993, and 1989 and 1990 growing seasons, respectively. Seasonal ET averaged 877 mm for the wheat, 578 mm for the sorghum, and 771 mm for the corn. Maximum daily ET rates exceeded 10 mm d^{-1} on several days, particularly for the wheat crops. Leaf resistance values for the Penman-Monteith equation were 135 s m^{-1} for wheat, 252 s m^{-1} for corn, and 280 s m^{-1} for sorghum for maximum ET with full ground cover (LAI > 3.0) and adequate soil water.

Keywords:

climate, corn, crop-water use, evapotranspiration, irrigation, lysimeters, potential ET, reference ET, sorghum, water balance, wheat

EVAPOTRANSPIRATION OF IRRIGATED WINTER WHEAT, SORHUM, AND CORN [1]

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ABSTRACT

Evapotranspiration (ET) is basic information required for irrigation scheduling and for crop growth simulation models, but many ET models have not been tested for their application to the Southern High Plains. In this study ET was measured for irrigated winter wheat (*Triticum aestivum* L.), sorghum (*Sorghum bicolor* (L.) Moench), and corn (*Zea Mays* L.) at Bushland, TX, in the semi-arid Southern High Plains for the 1989-90, 1991-92, and 1992-93; 1988 and 1993; and 1989 and 1990 cropping seasons, respectively, using weighing lysimeters that contained undisturbed monoliths 3 m by 3 m by 2.3 m deep of Pullman clay loam (Torrertic Paleustolls). Weather data from a nearby station were used to compute daily ET values for several widely used reference or potential ET equations and compared by linear regression with the measured ET values for periods of full-ground cover (LAI $\geq$ 3) and with adequate soil water to permit maximum ET. Mean seasonal was 877 mm for winter wheat, 771 mm for corn, and 578 mm for sorghum. Daily ET rates exceeded 10 mm d^{-1} for the sorghum crops only on a few days, exceeded 10 mm d^{-1} for corn for only a few days during a brief period of strong advection in 1990, and exceeded 10 mm d^{-1} for wheat on many days during the three seasons due to the high vapor pressure deficits and wind speeds at Bushland during the spring and early summer. The Penman-Monteith equation performed consistently better than other ET equations in estimating maximum daily ET rates for these crops. The leaf diffusion resistance (r_l) that permitted the best agreement between predicted and lysimetrically determined ET was 280 s m^{-1} for sorghum, 252 s m^{-1} for corn, and 135 s m^{-1} for wheat when using the relationship of $r_c = r_l/(0.5\ \mathrm{LAI})$ where LAI is the leaf area index and r_c is canopy resistance in s m^{-1}. These results indicate that the greater water use by irrigated corn compared with sorghum in this environment is due to the differences in planting date and growing season length. The even higher water use of irrigated winter wheat compared with corn and sorghum was due to its longer growing season, its lower leaf resistance, and the high evaporative demand in the spring in the Southern High Plains.

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INTRODUCTION

Winter wheat, corn, and sorghum are the principal irrigated crops in the northern Texas High Plains (over 87% of irrigated area), are major irrigated crops in the central Texas High Plains (over 54% of irrigated area), but are minor crops (less than 14% of irrigated area) in the southern Texas High Plains where cotton is the major irrigated crop (almost 80% of irrigated area) (Musick et al., 1990). Corn has one of the highest water requirements of the irrigated crops in the Southern High Plains (Musick et al., 1990). Sorghum and wheat are produced under full irrigation, limited irrigation, and dryland regimes. Corn, however, is mainly produced under full irrigation regimes (Musick and Dusek, 1980b). Recently, corn has been produced in the northern Texas High Plans as a dryland crop; however, dryland corn is risky to produce in this region and limited to sites with excellent preplant soil water conditions. The irrigation requirement supplements the 400 to 600 mm annual rainfall. Sprinkler irrigation is expanding in the region (Musick et al., 1988), and the declining well yields result in low irrigation capacities (flow rate per unit land area) (Musick and Walker, 1987). Sprinkler irrigation and low irrigation capacity demand precise irrigation management, particularly for corn (Howell et al., 1989).

Evapotranspiration (ET) measurement methods are described by Hatfield (1990), and weighing lysimeters are one of the most accurate methods to determine ET. Bowen ratio and eddy correlation methods are becoming more widely used (Fritschen and Simpson, 1989; Bausch and Bernard, 1992; and Dugas et al., 1991). The Bowen ratio method makes several critical assumptions, relies heavily on the precision of net radiation measurement, and has limitations when the ratio is - 1.0. Eddy correlation equipment is becoming more robust for seasonal deployment (Kizer et al., 1990). Soil water balance is one of the main methods used to determine crop water use. Soil water balance relies heavily on uniform soil water contents for reliable samples, the precision of the water input measurements, and critical information to characterize deep percolation and runoff. Carrijo and Cuenca (1992) indicated neutron probes (assuming deep percolation and runoff were minimized) could be used to determine ET rates over several days to perhaps a week with considerable accuracy.

Jensen et al. (1990) reviewed methods for estimating ET and recommended the Penman-Monteith equation (Monteith, 1965) as presented by Allen et al. (1989) as the preferred method for daily reference ET. They proposed that 0.5 m be the "standard" alfalfa height and 0.12 m be the "standard" height for grass for reference ET models. Burman et al. (1980), Hatfield (1990), Hatfield and Fuchs (1990), Doorenbos and Pruitt (1977), and Jensen (1974) also review ET computation methods. Reference ET, in practice, is a hypothetical value depending on weather data and the following specific crop parameters: 1) albedo; 2) emissivity; 3) crop height; and 4) leaf resistance. The first two parameters affect net radiation and energy partitioning into soil heat flux. Crop height affects the aerodynamic characteristics of the crop that influence sensible and latent heat exchange between the crop canopy and the atmosphere. Leaf resistance affects the reference crop surface resistance to latent heat transfer to the atmosphere. Energy partitioning of net radiation (R_n) into soil heat flux (G) is implicitly assumed to be a small component for reference crops, and G is usually estimated by simple relationships to air temperature or R_n itself. Penman (1956) defined potential ET as that from a short, fully transpiring grass. Van Bavel (1966) clarified Penman's concept and characterized the defining parameter of "potential" evaporation as a surface vapor pressure that could be determined simply as the saturated vapor pressure at the temperature of the surface.

One goal of ET research has been the identification and evaluation of methods for estimation ET that use readily available data (Hatfield, 1988; Heermann, 1988; and Saxton and Cordery, 1988). The summary by Jensen et al. (1990) is the most complete recent treatment of ET methodology, but earlier reviews by Jensen (1974) and particularly that by Brutsaert (1982) and Doorenbos and Pruitt (1977) provide additional information.

Steiner et al. (1991) reviewed a number of evaluations of ET models. Local calibration (Jensen, 1974) is laborious. Skidmore et al. (1969) reported good agreement for the Van Bavel (1966) equation compared to Bowen ratio determined ET for moderate wind speeds (< 1.5 m s^{-1}), but for higher wind speeds the model over-predicted ET. Shouse et al. (1980) reported that the ET model of Doorenbos and Pruitt (1977) and that of Jury and Tanner (1975) performed well at Riverside, CA. Jamieson (1982) found the Priestley and Taylor (1972) equation performed well in predicting maximum water use by barley in New Zealand for 30-min values, but it under-predicted by 9% for 24-h values. The combination equation of Penman (1948) over-predicted by 18%, and the Van Bavel (1966) ET model more seriously over-predicted in his windy, humid environment. Allen (1986) reported excellent agreement in predicting lysimeter observed ET from three sites with a Penman-Monteith equation (Monteith, 1965). Phene et al. (1986) found the Penman (1948) wind function and combination equation over-predicted ET of grass at Fresno, CA, by about 9%, while the Priestley and Taylor (1972) equation under-predicted grass ET by 13%. Meyer et al. (1987) reported an underestimation of ET of wheat by the combination equation with a locally derived wind function and found nighttime ET strongly related to wind speed. Steiner et al. (1991) reported that combination equations over-predicted maximum ET of sorghum at Bushland, TX; that a Penman-Monteith equation performed well; that the Priestley-Taylor equation performed satisfactorily; but that the Jensen-Haise equation over-predicted ET of sorghum. Kizer et al. (1990) used an hourly form of the combination equation in the fashion of Pruitt and Doorenbos (1977) and reported, similarly, the need for a nighttime and a daytime wind function. Jensen et al. (1990) evaluated a number of ET methods for several sites and concluded that the Penman-Monteith equation patterned after Allen (1986) and Allen et al. (1989) performed well and recommended its adoption for reference ET methods.

The main difficulty in using the Penman-Monteith equation is characterizing the canopy surface and atmospheric diffusion resistances. Traditionally, the canopy resistance has been estimated from net radiation as described by Monteith

(1965) or by using leaf area index (LAI) which was found to vary inversely with canopy resistance (Monteith, 1965). Allen (1986) reported good agreement between lysimeter determined ET values and estimates by the Penman-Monteith equation using both net radiation and LAI. Later, Allen et al. (1989) and Jensen et al. (1990) proposed characterizing canopy resistance simply by LAI. Idso (1983) using the Penman-Monteith equation and an empirical baseline based on infrared thermometry illustrated that the canopy resistance for a well-watered crop would depend mainly on net radiation. Steiner et al. (1991) demonstrated that independent baseline parameters and Idso's equation for canopy resistance performed well in estimating canopy resistance for well-irrigated, full-cover sorghum.

The objectives of this paper are 1) to report and summarize daily and seasonal ET data for irrigated winter wheat, corn, and sorghum at Bushland, TX, for several seasons and 2) to analyze the maximum daily ET values compared with various ET computation methods for the full-cover, well-watered crops.

MATERIALS AND METHODS

The study was conducted at the USDA-ARS Laboratory at Bushland, TX (35° 11′ N lat.; 102° 06′ W long.; 1,170 m elev. above MSL). The ET of the crops was measured with weighing lysimeters (Marek et al., 1988) during the 1989-90, 1991-92, and 1992-93 seasons for winter wheat, the 1988 and 1993 seasons for sorghum, and the 1989 and 1990 seasons for corn. The irrigated winter wheat crop coefficient data are described in more detail in Howell et al. (1993). Two lysimeter fields were planted to each crop in each season. In 1988, both sorghum fields were maintained well watered, and in 1989 and 1990 both of the corn fields were maintained well watered. In the other years, one field was always fully irrigated to meet ET demands and only those data are reported herein. Each lysimeter field is approximately 44,000 m^2 (210 m E-W by 210 m N-S), and the lysimeter is centered in each field. The predominate wind direction is SW to SSW, and the unobstructed fetch in this direction exceeds 1 km.

Table 1 summarizes the agronomic and management details. The wheat was planted flat in all years, but the corn and sorghum were grown on raised beds. All field operations were performed with standard 4.6 m wide row-crop field equipment and standard 4.3 m wide combines, except in the immediate 30-m^2 area at each lysimeter where hand-cultural methods were required. Fertility and pest control were applied uniformly to the field area. Irrigations were applied with a 10-span lateral move sprinkler system (Lindsay [4/]) with an end-feed hose and above-ground, end guidance cable. The sprinkler system was aligned N-S, irrigated

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[4/] Mention of trade manufacturer names is made for information only and does not imply an endorsement, recommendation, or exclusion by USDA-Agricultural Research Service.

E-W or W-E. The system was equipped with gooseneck fittings and spray heads (Senninger Super Spray 360°) with medium grooved spray plates on drops located about 1.5 m above the ground and 1.52 m apart. The drops could be converted to LEPA (low energy precision application) heads placed about 0.3 m above the ground. Impact sprinklers (Senninger model 3006) with a 6° discharge angle were also located at 6 m spacing along the lateral move pipeline. The individual irrigation could be selected by manual valves. All three sprinkler irrigation modes (impact sprinkler, spray heads, and LEPA) were used at different times. The wheat and sorghum crops were not irrigated with LEPA, however. The irrigations were scheduled for the fully irrigated fields to maintain the soil water profile adequately supplied with water to minimize soil water deficits to avoid reducing ET or yield. The soil water content profile was maintained at about 80% or greater of the extractable soil water.

Plant samples from 1.5-m^2 areas were obtained periodically to measure crop development. These field samples were taken at sites about 10 to 20 m away from the lysimeters in areas of the field representative of the lysimeter vegetation. LAI and aboveground dry matter (DM) were measured. Final grain yield was measured by harvesting all the heads or ears in the lysimeter (9 m^2), and dry matter and grain yield at harvest were measured from adjacent plant samples. Wheat and sorghum head samples were threshed with a head thresher in the laboratory, and the ears were hand shelled. In addition, field yield strips were cut by a combine in both E-W and W-E passes in the center of each irrigation span (10 spans), and the grain was weighed with a field grain cart equipped with a scale. Grain samples were obtained from the combined grain and oven dried to determine the moisture content. All grain yield data are reported at 14% wc (wb) for the wheat and sorghum and 15.5% wc (wb) for the corn.

Solar radiation, wind speed, air temperature, dew point temperature, relative humidity, precipitation, and barometric pressure were measured at an adjacent weather station (Dusek et al., 1987) with an irrigated grass surface (cool season lawn mixture containing bluegrass, perennial rye-grass, etc.). The weather station is 1,520 m^2 in area including the irrigation border surrounding the level plot. The weather station is immediately E of the east lysimeter field and slightly S of the N-S center of the lysimeter fields. The weather station grass was routinely mowed to a height of about 0.12 m and was fertilized and irrigated as needed to maintain vigor. The 100-m radius area immediately S and SE from the weather station (direction of predominate winds) was in various fallow and wheat cover crops during these studies. Immediately NE of the weather station, a 3-span center pivot field was planted to various irrigated crops including corn and sorghum in 1989 and 1990 and corn in 1992 and 1993, but was in summer fallow in 1991 for perennial weed control. Solar radiation was measured with a pyranometer (Eppley PSP); 2-m height wind speed was measured with a cup anemometer (Met-One 014A); air temperature, dew point temperature, and relative humidity were measured in a standard Cotton Belt shelter (1.5 m above ground) with a variety of instruments (Dusek et al., 1993) -- Phys-Chem Campbell Scientific model 207, YSI model 9400 dew cell, Hygrometrix Campbell Scientific XN217, Rotronic MP100, R.M. Young model 41407 dew cell, and a ventilated psychrometer with a ceramic wet-bulb wick (Lourence and Pruitt, 1969); and barometric pressure was measured in the instrument shelter with a pressure transducer (YSI model 2014). All transducers were measured at 0.167-Hz (6 s) frequency by a Campbell Scientific CR-7X data logger, signals were averaged for 15 min, and two 15-min means were composited into 30-min means. Daily (24 h) averages, maximum, or minimum values were determined from the 0.167-Hz samples. Data were transferred daily via telephone modem from the CR-7X to a laboratory personal computer. Daily solar radiation (R_s), maximum (T_{max}) and minimum (T_{min}) daily air temperature, average daily dew point temperature (T_{dew}), 2-m wind speed (U_{2g}) and average daily barometric pressure (P_b) were used in the subsequent calculations of reference ET.

Lysimeter mass was determined using a Campbell Scientific CR-7X data logger to measure and record the lysimeter load cell (Alphatron S50) signal at 0.5-Hz (2 s) frequency. The load cell signal was averaged for 15 min, and composited to 30-min means. Daily ET was determined as the difference between lysimeter mass losses (from evaporation and transpiration) and lysimeter mass gains (from irrigation, precipitation, or dew) divided by the lysimeter area (9 m^2). ET for each 24-h period was multiplied by 1.02 to adjust the lysimeter area to the mid point between the two walls (10 mm air gap; 9.5 mm wall thickness; 9.18 m^2 area instead of 9.00 m^2 area). This correction would be applicable for full-cover crops, but it would not be necessary for bare soil conditions. Nevertheless, it was applied to all data uniformly.

Daily ET data used in this analysis represented the period after full ground cover (defined by the leaf area index in m^2 m^{-2} exceeding 3.0), when the soil was amply filled with water to avoid restricted crop water uptake, and when no irrigations, drainage, or rainfall occurred to avoid any possible lysimeter mass measurement problems. These ET data were combined with the weather station data on those days and the crop height and LAI. For the wheat crops, the data set included 84 days; for the corn crops, it included 148 days; and for the sorghum crops, it included 112 days.

Daily ET for each crop was computed as

$$ET_c = \frac{\Delta(R_n + G)/\lambda + (8.64 x 10^4)(\rho\, C_p/\lambda)(e_a - e_d)/r_a}{[\Delta + \gamma(1 + r_c/r_a)]} \qquad ...[1]$$

where ET_c is the estimated crop ET in mm d^{-1}, Δ is the slope of the saturated vapor pressure curve ($\partial e_s/\partial T$) in kPa °C^{-1}, R_n is net radiation in MJ m^{-2} d^{-1}, G is soil heat flux in MJ m^{-2} d^{-1} (positive when heat flux is toward the surface), λ is latent heat of vaporization in MJ kg^{-1}, ρ is air density in kg m^{-3}, C_p is specific heat of moist air in MJ kg^{-1} °C^{-1} [1013 J kg^{-1} °C^{-1}], e_a is mean saturated vapor pressure in kPa at T_{max} and T_{min} {$e_a = [e_s(T_{max}) + e_s(T_{min})]/2$ where $e_s(T)$ is saturated vapor pressure in kPa at temperature T}, e_d is saturated vapor pressure in kPa at mean daily dew point temperature (T_{dew}), γ is the psychrometric constant in kPa °C^{-1} [C_p P_b)/(0.622 λ)], r_a is aerodynamic canopy resistance in s m^{-1}, and r_c is canopy surface resistance in s m^{-1}. In eq. [1], the parameters were calculated using the ASCE Manual No. 70 equations (Jensen et al., 1990) based on Allen (1986), Wright (1982, 1988), and Allen et al. (1989). R_n was measured at each lysimeter with miniature net radiometers (Micromet, Inc. before 1989 and REBS, Inc. after 1990). G was measured at 100 mm depth before 1989 (Micromet, Inc., soil heat flux plates) and after 1990 at 50 mm depth (REBS soil heat flux plates). Soil heat flux was corrected for thermal storage in the soil layer above the plates as

$$G = G_z + [2.4\, z\, (T_0 - T_{24})] \qquad ...[2]$$

where G is soil heat flux (positive toward the surface) at the soil surface in MJ m^{-2} d^{-1}, G_z is the measured soil heat flux in MJ m^{-2} d^{-1} at depth z in m, and T_0 and T_{24} are the mean soil temperatures in °C in the layer above the heat flux plates (0 to z) at the beginning of the day and the end of the day, respectively. The parameter 2.4 MJ m^{-3} °C^{-1} is the soil specific heat computed for the Pullman soil based on its constituents (minerals, organic matter, etc.) for a soil water content of 0.25 m^3 m^{-3}, which we assumed to be constant for these well-watered days with frequent sprinkler irrigations. The aerodynamic canopy resistance was estimated following Allen et al. (1989) and Steiner et al. (1991) as

$$d_g = 0.667\ h_g \qquad ...[3]$$

$$Z_{omg} = 0.123\ h_g \qquad ...[4]$$

$$Z_{ohg} = 0.1\ Z_{omg} \qquad ...[5]$$

$$U_{2c} = U_{2g}\ \frac{\ln\left[\dfrac{(Z_{ab} - d_g)}{Z_{omg}}\right] \ln\left[\dfrac{(CH+2-d_c)}{Z_{omc}}\right]}{\ln\left[\dfrac{(Z_{ab} - d_c)}{Z_{omc}}\right] \ln\left[\dfrac{(2-d_g)}{Z_{omg}}\right]} \qquad ...[6]$$

$$r_a = \frac{\ln\left[\dfrac{(CH + 2 - d_c)}{Z_{omc}}\right] \ln\left[\dfrac{(CH + 2 - d_c)}{Z_{ohc}}\right]}{k^2\ U_{2c}} \qquad ...[7]$$

where d_g is the zero-plane displacement height in m for the grass, h_g is the height of the grass in m [0.12 m], Z_{omg} is the momentum roughness length in m for the grass, Z_{ohg} is the heat roughness length in m for the grass, U_{2c} is the wind speed in m s^{-1} extrapolated from 2 m over the grass (U_{2g}) to 2 m over the crop, Z_{elb} is an equilibrium height in m [taken as 10 m following Steiner et al. (1991)], CH is the crop height in m, d_c is the zero-plane displacement height in m for the crop, Z_{omc} is the crop momentum roughness length in m, Z_{ohc} is the heat roughness length in m for the crop, and k is von Karman's constant [0.41]. Z_{omc}, Z_{ohc}, and d_c were estimated similarly to eq. [3] through [5] using CH instead of h_g. The canopy surface resistance was estimated as

$$r_c = \frac{r_l}{(0.5\ LAI)} \qquad \ldots[8]$$

where r_l is the leaf resistance in s m^{-1} and LAI is leaf area index in m^2 m^{-2} following Allen et al. (1989). The leaf resistance, r_l, was varied from 100 s m^{-1} to 250 s m^{-1}. Allen (1986), Allen et al. (1989), and Jensen et al. (1990) recommended r_l as 100 s m^{-1}, but Steiner et al. (1991) reported a r_l of 163 s m^{-1} fit maximum lysimeter measured water use for full-ground cover sorghum at Bushland. We did not attempt to optimize r_l to fit our data, but we did determine the r_l magnitude that equated the mean Penman-Monteith ET to the measured ET_l. In addition, r_c was estimated using the well-watered baseline method from Idso (1983) as adapted and tested by Steiner et al. (1991) as follows

$$r_c = \left[\frac{[1-b(\Delta+\gamma)]}{(1-b\,\Delta)}\right]\left[\frac{(a\ \rho\ C_p)}{(b\ \gamma\ R_{nf})}\right] \qquad \ldots[9]$$

where R_{nf} is the net radiation flux in W m^{-2} and a and b are empirical constants defined by the well-watered baseline given as

$$T_c - T_a = a - b\ VPD \qquad \ldots[10]$$

where T_c is crop canopy temperature in °C, T_a is air temperature in °C, and VPD is ambient vapor pressure deficit in kPa. Values for a and b were estimated for each crop from the following:

Crop	Reference	a(°C)	b(°C kPa^{-1})
Winter Wheat	Howell et al. (1986)	1.08	2.09
Sorghum	O'Toole and Hatfield (1983)	2.53	1.96
Corn	Idso (1982)	3.11	1.97

The ET for this Idso-Penman-Monteith equation was called ET_{pmi}.

Three forms of the combination equation (Penman, 1948) were also used to compute "reference" or potential ET as follows:

$$ET_{p48} = \frac{\Delta(R_n+G)/\lambda + \gamma\ (e_o-e_d)\ (6.43+3.453\,U_{2g})/\lambda}{(\Delta+\gamma)} \qquad ...[11]$$

$$ET_{fao} = \frac{\Delta(R_n+G)/\lambda + \gamma\ (e_o-e_d)\ (6.43+5.556\,U_{2g})/\lambda}{(\Delta+\gamma)} \qquad ...[12]$$

$$ET_{kim} = \frac{\Delta(R_n+G)/\lambda + \gamma\ (e_a-e_d)\ (4.82+6.385\,U_{2g})/\lambda}{(\Delta+\gamma)} \qquad ...[13]$$

where R_n and G were measured and described earlier and ET_{p48}, ET_{fao}, and ET_{kim} represent the wind functions derived by Penman (1948) for grass, by Doorenbos and Pruitt (1977) for grass, and by Wright and Jensen (1972) for alfalfa, respectively. Vapor pressure deficit (VPD) was computed similarly to that shown in the ET_c equation [eq. 1] for ET_{kim} (VPD = e_a - e_d), but the ET_{p48} and ET_{fao} equations [eqs. 2 and 3] used e_o computed at mean air temperature [$T = T_{min} + T_{max})/2$; $e_o = e_s(T)$] to compute the VPD (VPD = e_o - e_d). Both VPD calculation methods perform well at Bushland (Howell and Dusek, 1994; and Steiner et al., 1991); however, VPD methods can be expected to affect the performance of the combination equation, particularly, in the Great Plains (Sadler and Evans, 1989). The equilibrium "potential" ET for non-advective conditions was computed using the Priestley and Taylor (1972) equation as

$$ET_{pt} = \frac{1.26\ \Delta(R_n+G)/\lambda}{(\Delta+\gamma)} \qquad ...[14]$$

The radiation-temperature based ET equation developed by Jensen and Haise (1963) and modified as described later in Jensen et al. (1990) was computed as

$$ET_{jh} = C_t\,(T - T_x)\ R_s/\lambda \qquad ...[15]$$

where C_t and T_x are coefficients taken as 0.0234 °C^{-1} and -8.76 °C, respectively, following Steiner et al. (1991) for Bushland conditions. These equations were coded in a spreadsheet program, and components were verified with REF-ET, vers. 2.1 (Allen, 1990). Linear regressions were computed among ET estimates for all these models [eqs. 1, 11 through 15] and ET_l as measured by the lysimeters.

Empirical wind functions were fit for each crop using eq. 13 as follows

$$f(U_2) = \frac{ET_l\,(\Delta+\gamma) - \Delta\ (R_n+G)\ /\lambda}{\gamma\ (e_a - e_d)} \qquad ...[16]$$

RESULTS AND DISCUSSION

The climatic conditions for the winter wheat seasons (Howell et al., 1993) are extremely divergent from cold to hot, from windy to calm, and humid to very dry. These conditions and climatic diversity are common in the Great Plains. Table 2 provides a summary of the 24-h climatic parameters and crop characteristics for the selected periods with full-ground cover and well-watered conditions conducive to maximum ET. The winter wheat data cover one of the broadest ranges in temperature from 2.4 to 31.6°C. All the data sets included mean 2-m wind speeds exceeding 6 m s^{-1}.

Winter Wheat

Crop development is shown in Figure 1 for the three wheat seasons. The wheat cultivar was changed in each season (Table 1) for various reasons. TAM-200 (used in 1989-90) is somewhat susceptible to winter kill, and we wanted to avoid any potential problems (although we had no problems in 1989-90). TAM-107 (used in 1991-92) grew excessively tall and lodged under the conditions of 1991-92 under high management inputs. Other plots at Bushland with TAM-107 also lodged badly that year. Mesa (used in 1992-93) is a somewhat shorter cultivar while sacrificing some yield potential. The maximum LAI in 1989-90 and 1992-93 barely reached or exceeded 4.0; however, DM exceeded 1.6 kg m^{-2} in each year indicative of good wheat crops (Musick and Porter, 1990). The LAI was the highest in 1991-92, and the DM exceeded 2.0 kg m^{-2} with a combine harvested yield of 680 g m^{-2}. The lysimeter grain yield in that year was only 379 g m^{-2}, due to the lodged crop. However, grain yields in 1989-90 and 1992-93 were typical of irrigated plot yields (535 and 600 g m^{-2}, respectively). Temperatures during grain filling can dramatically affect grain-fill duration in this environment (Wiegand and Cuellar, 1981; Howell et al., 1993). Grain-fill periods were substantially shorter in 1989-90 and 1992-93 compared with the longer grain-fill period in 1991-92, a cooler season.

Daily ET for winter wheat is shown in Figure 2 for each season. Fall ET rates were variable depending on fall conditions (planting date, temperatures, etc.). Winter-time ET rates in the 1989-90 season were low due to the late planting, dry fall conditions, and limited crop development going into winter. Winter-time ET rates seldom exceeded 1 or 2 mm d^{-1}, but these ET rates can accumulate to substantial ET values over the nearly two-month winter (Dec. and Jan.). By mid February, ET rates and crop growth began to accelerate. ET rates are generally maximum at heading. In all years, maximum daily ET rates exceeded 12 mm d^{-1} on several occasions. The high ET rates exceeding 14 mm d^{-1} in 1991-92 just after heading (and before any lodging) are discussed in Howell et al. (1993) and were mainly caused by high vapor pressure deficits and winds. Physiological maturity (PM) is difficult to determine in wheat because it does not form a black-layer like corn or sorghum. Generally, ET rates dropped dramatically with senescence at PM.

Seasonal ET values (Table 1) were 791, 909, and 939 mm in the 1989-90, 1991-92, 1992-93 seasons, respectively. These values are greater than those summarized by Musick and Porter (1990) for Bushland (mean was 710 mm) found by Jensen and Sletten (1965a), Schneider et al., (1969), Musick and Dusek (1980a), and Eck (1988) and were most likely influenced by growing season environments or the more frequent sprinkler irrigations.

Table 3 summarizes the comparisons between ET methods for winter wheat. A r_l value of 135 s m^{-1} provided a mean ET_{pm} similar to that measured by the lysimeters. The ET_{pmi} performed well (without any fitting). The Penman equation under-predicted ET while the other combination equations over-predicted ET of wheat. The radiation-temperature based equations (Jensen-Haise and Priestley-Taylor) under-predicted maximum wheat ET. All ET equations, except the Penman-Monteith based equations, had significant intercepts (biases). Figure 3 shows the comparison of the fitted Penman-Monteith ET equation for a r_l of 135 s m^{-1} for full-cover wheat compared with the lysimeter measured ET. The $S_{y/x}$ was 1.05 mm d^{-1} for the regression, and the lysimeter ET extended over the range from less than 3 mm d^{-1} to greater than 13 mm d^{-1}.

Sorghum

Figure 4 shows the crop development in the two years. In 1988, the hybrid was a medium maturity hybrid which is grown under both irrigation and dryland in this region. It produced a maximum LAI slightly exceeding 4.0 and a DM exceeding 1.4 kg m^{-2}. The grain yield averaged 845 g m^{-2} (Table 1) for the two lysimeters in that year and was about 12% greater than the field combined yield. In 1993, the earlier planting and longer maturity hybrid (Table 1) increased the maximum LAI to over 5.0 and DM to over 2.0 kg m^{-2} and grain yield to 898 g m^{-2}. These yields are typical of the mean irrigated sorghum performance tests summarized for the Texas High Plains for 1981-1985 of 803 g m^{-2} (Krieg and Lascano, 1990).

Daily ET rates are shown in Figure 5 for the two sorghum seasons. ET rates approached maximum values at the early boot stage when LAIs maximized. One day had an ET rate exceeding 11 mm d^{-1} in 1988, and none exceeded 10 mm d^{-1} in the 1993 season. ET rates declined following heading but not nearly like those of the wheat crops, because sorghum is a perennial species and does not senesce or go dormant. In this environment, sorghum will continue to grow (even past harvest) unless terminated by chemicals, tillage, or freezing. In both seasons, ET rates were still about 4 mm d^{-1} even at PM.

Seasonal ET (Table 1) averaged 549 mm in 1988 and was 637 mm in 1993 when the earlier planting and longer maturity hybrid were studied. Jensen and Sletten (1965b) reported a mean ET of irrigated sorghum of 559 mm at Bushland; Stewart et al. (1983) reported a mean fully irrigated ET for sorghum of 619 mm at Bushland; Musick et al. (1963) reported a range of maximum ET for sorghum from studies at Garden City, KS, of 584 to 635 mm; and Chaudhuri and Kanemasu

(1985) reported a range of ET from 549 to 584 mm for different hybrids at Manhattan, KS. The seasonal ET values at Bushland reflect these ranges, and clearly show that sorghum has much lower ET under full irrigation than wheat or corn (see next discussion on corn).

Table 3 summarizes the comparisons between ET methods for sorghum with full ground cover. A r_l value of 280 s m^{-1} provided a mean ET_{pm} similar to that measured by the lysimeters. The ET_{pmi} performed well (without any fitting), but not as well as reported for our 1987 and 1988 sorghum data analyzed by Steiner et al. (1991), but it did have a minimum bias (intercept) and a relatively low $S_{y/x}$. Like Steiner et al. (1991) reported, all the combination equations over-predicted maximum ET rates for sorghum, and had significant and large off-set biases (intercepts). The Priestley-Taylor equation did well in representing the mean measured ET, but it had a large intercept and a low slope. Figure 6 shows the maximum daily ET values for sorghum for the fitted Penman-Monteith equation for a r_l of 280 s m^{-1} for the full-cover conditions compared with the measured lysimeter values. The $S_{y/x}$ was 0.66 mm d^{-1} for the regression, and the lysimeter ET extended from less than 3 mm d^{-1} to slightly greater than 10 mm d^{-1}.

Corn

Figure 7 shows the crop development in the two years. The crops grew slightly differently in both years on these two fields. In 1989, the north field was a little taller and more vigorous, while in 1990 the south field was a little taller and more vigorous, but the differences were relatively small. The LAI and DM were plotted separately for the two fields in 1990 to show this difference and variability. Maximum LAI exceeded 5.0 in both years, and in 1990 the SE field LAI approached 6.0. LAI declined after tasseling each year and dramatically declined at about mid-grain fill with senescence. Maximum DM was 2.2 kg m^{-2} in 1989, and it exceeded 2.4 kg m^{-2} in 1990. Mean lysimeter grain yield was 1216 g m^{-2} in 1989 and 1238 g m^{-2} in 1990, and mean combined yields were 976 and 1097 g m^{-2}, respectively, somewhat less than those suggested by Rhoades and Bennett (1990) of 1100 to 1500 g m^{-2} to be expected for irrigated corn. But our yields are similar to those reported by Musick and Dusek (1980b), Eck (1984), and Howell et al. (1989) for fully irrigated corn yields at Bushland.

Daily ET rates for irrigated corn are shown in Figure 8 for both seasons. The maximum ET rate in 1989 occurred a few days before tasseling at maximum LAI (Fig. 7). In 1990, however, an extended period of regional advection increased the ET rates prior to tasseling (but LAIs were above 3.0). About midway through the grain-fill period, ET rates began to decline in response to the declining LAI and developing crop senescence as PM approached. One day had an ET rate in excess of 11 mm d^{-1} in 1989, but several days had those magnitude rates in 1990 during the period of advected heat. Interestingly, both corn and sorghum have considerably lower maximum ET rates during mid summer at Bushland than winter wheat does in the late spring and early summer. This is due to the climatic pattern of low dew point temperatures and high wind speeds in the spring, while during the summer both wind speeds and vapor pressure deficits are more moderate even though air temperatures may be higher. In addition, clear sky conditions may occur more often in the spring before strong convective cloud patterns establish.

Seasonal ET values (Table 1) averaged 740 and 802 mm for 1989 and 1990, respectively. Fully irrigated corn water use at Bushland has been reported to vary from 670 to 790 mm by Musick and Dusek (1980b), from 783 to 1003 mm by Eck (1984) for surface irrigation and 838 mm by Howell et al. (1989) for sprinkler irrigated corn. Again, the measured seasonal ET for corn is typical of the variations reported. Interestingly in both years, the lysimeter with the greatest grain yield also had the largest ET.

Table 3 summarizes the relationships between measured ET for full-cover corn and computed ET. A r_l of 252 s m^{-1} provided a mean ET_{pm} similar to that measured by the lysimeters. The ET_{pmi} performed well (without any fitting), but it still under-predicted the measured ET, although it was the only method for corn not to have a significant bias (intercept). The combination equations all over-predicted maximum corn water use, but the Penman (1948) equation predictions were relatively similar to the measured values (within 5%). The Jensen-Haise equation had a similar mean value, but it had a large intercept and small slope. Figure 9 shows the fitted Penman-Monteith ET equation compared to the measured ET values for irrigated corn. The $S_{y/x}$ was 0.73 mm d^{-1}, and the measured ET values ranged from < 3 mm d^{-1} to > 12 mm d^{-1}. The ET_{pm} did not fit the few largest measured ET values for corn as well as it did for the wheat or sorghum data sets. It could be related to our methods of interpolating LAI values, but it is most likely due to diurnal effects of winds and vapor pressure deficits.

Wind Functions

The wind functions fit to the lysimeter measured maximum ET values for the specific crops are summarized below where the intercept is in mm d^{-1} kPa^{-1}, the slope is in mm d^{-1} kPa^{-1} m^{-1} s, and $S_{y/x}$ is in mm d^{-1} kPa^{-1}:

Crop	Intercept	Slope	r^2	$S_{y/x}$
Wheat	2.29	1.51	0.406	2.43
Sorghum	1.73	0.51	0.054	2.09
Corn	2.74	0.92	0.223	2.19

None of these wind functions fit the data very well which is similar to the conclusions reported by Steiner et al. (1991). Actually, the wheat wind function is not very different from the original Penman (1948) wind function for grass [$f(U) = 2.63 + 1.42\ U_{2g}$, where U_{2g} is in m s^{-1}]. The slopes were considerably lower than the 2.72 mm d^{-1} kPa^{-1} reported by Steiner et al. (1991) for sorghum or the 2.31 mm d^{-1} kPa^{-1} reported by Phene et al. (1986) for grass as well as those used in eqs. [11] through [13]. The inability to fit accurate wind functions may be due to differing daytime and nighttime wind regimes, VPD, and/or day- and night-time soil water evaporation rates. It is interesting that we were able to fit relatively good functions to $1/r_a$ for these conditions with r_a determined by eq. [7] for its particular crop. The resulting equations are given below:

Crop	Equation	r^2	$S_{y/x}$ $m\ s^{-1}$
Wheat	$1/r_a = 0.00789\ U_{2g}$	0.968	0.00684
Sorghum	$1/r_a = 0.00996\ U_{2g}$	0.988	0.00454
Corn	$1/r_a = 0.00872 + 0.0107\ U_{2g}$	0.792	0.00701

These equations are similar to the form proposed by McIlroy and Angus (1964) and Thom and Oliver (1977). Later, the more theoretical transfer coefficient was introduced by Van Bavel (1966) and Businger (1966) adopting the adiabatic wind function.

SUMMARY AND CONCLUSIONS

Evapotranspiration rates from irrigated crops of winter wheat, sorghum, and corn were affected strongly by the dynamic environmental conditions experienced in the Southern High Plains. Wheat has a high ET water use because it has a low canopy resistance, grows during a hot, dry, windy part of the year, and has a long growing season. Corn has a slightly higher maximum peak ET rate than sorghum (although both are C_4 crops) because it has a slightly lower canopy resistance (252 compared to 280 s m^{-1} for sorghum) and is a little rougher (aerodynamically) because it is taller. Seasonal ET for corn is greater than for sorghum because of these facts, and also because corn has a longer growing season. Seasonal ET for wheat averaged 877 mm while corn and sorghum averaged 771 and 578 mm, respectively, for these seasons.

Peak daily ET values for wheat exceeded those for corn or sorghum at this location. Peak ET rates for these crops are comparable to the maximum measured values of 14.2 mm d^{-1} in Nebraska (Rosenberg and Verma, 1978) and exceeded the maximum values of 11.0 mm d^{-1} (Wright, 1988) for alfalfa in Idaho.

The leaf resistance values of 135, 280, and 252 s m^{-1} for wheat, sorghum, and corn, respectively, resulted in matching the mean lysimeter-measured ET using the Penman-Monteith equation. The crop specific (and perhaps location specific) well-watered baseline from Idso (1983) performed rather well in estimating r_c for these crops across a wide range of conditions. It certainly permits the base valve of r_l to be determined easily, and then this value could be further evaluated as necessary. Of course, the apparent disagreement between maximum crop ET and computed ET could be characterized by empirical crop coefficients. Wright (1982), Burman (1980), and Jensen et al. (1990) indicate that full cover corn and wheat have similar ET rates as reference alfalfa (peak crop coefficient for alfalfa reference ET for wheat at Kimberly, ID, was 1.0 and 0.95 for corn); however, sorghum has not been directly compared to alfalfa. At Davis, CA, sorghum ET was 8% more than grass ET (peak crop coefficient for grass reference ET for sorghum was 1.08). Seasonal differences in crop development (Neale et al., 1989) as well as effects of environmental parameters which differentially affect crop and reference ET (Jagtap and Jones, 1989) need further evaluation.

Combination reference ET equations with their traditional wind functions over-predict maximum crop ET rates at this location because of the higher wind speeds and diurnal wind and vapor pressure deficit patterns. Instantaneous ET equations offer some potential hope in minimizing these problems (Howell et al., 1993), but they require additional inputs and perhaps additional complexities (Shuttleworth and Wallace, 1985; Shuttleworth and Gurney, 1990). Simpler ET models using mainly temperature and radiation inputs (Jensen-Haise and Priestley-Taylor) should be used with some degree of caution in this environment as also found by Steiner et al. (1991).

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Table 1. Agronomic and management information.

	SORGHUM		CORN		WINTER WHEAT		
PARAMETER	1988	1993	1989	1990	1989-90	1991-92	1992-93
Lysimeter Field(s)	NW & SW	NE	NE & SE	NE & SE	NW	NE	SW
Row Spacing (m)	0.76	0.76	0.76	0.76	0.25	0.25	0.29
Row Direction	E-W	E-W	E-W	E-W	E-W	N-S	E-W
Previous Crop	Sorghum	Wheat Fallow	Sorghum	Corn	Sorghum Fallow	Corn Fallow	Sorghum Fallow
Cultivar	DK-41Y	DK-56	PIO 3124	PIO 3124	TAM-200	TAM-107	MESA (Agripro)
Planting Date	06/20 [172] 1/	05/27 [147]	04/26 [116]	05/09 [129]	10/10/89 [283]	09/27/91 [270]	09/29/92 [273]
Emergence Date	06/27 [179]	06/03 [154]	05/07 [127]	05/18 [138]	10/18/89 [291]	10/07/91 [280]	10/09/92 [283]
Heading Date	08/16 [229]	07/27 [208]	07/22 [203]	07/26 [207]	05/09/90 [129]	04/27/92 [118]	05/05/93 [125]
Anthesis Date	08/22 [235]	08/05 [217]	08/01 [213]	08/03 [215]	05/16/90 [136]	05/08/92 [129]	05/13/93 [133]
Phys. Mat. Date	10/01 [275]	09/30 [273]	10/10 [283]	09/21 [264]	06/14/90 [165]	06/19/92 [171]	06/21/93 [172]
Harvest Date	11/14 [319]	10/05 [278]	10/24 [298]	10/29 [302]	06/26/90 [177]	07/06/92 [188]	06/28/93 [179]
Plant Dens. (# m^{-2})	16	20	6	6	190	193	131
Fert. [g(N) m^{-2}]	12	11	16	25	13	11	8
Lys. Yield 2/ (g m^{-2})	786 NW 903 SW	898 NE	1237 NE 1194 SE	1148 NE 1327 SE	535 NW	379 3/ NE	600 SE
Lys. DM (g m^{-2})	1439 NW 1652 SW	2006 NE	2168 NE 2175 SE	2127 NE 2177 SE	na 4/	1588 NE	na 4/
Combine Yield (g m^{-2})	726 NW 782 SW	1009 NE	1005 NE 947 SE	1051 NE 1142 SE	520 NW	680 NE	538 SE
Field Dry Matter (g m^{-2})	1687 NW 1612 SW	2002 NE	1984 NE 2212 SE	2280 NE 2560 SE	1316 NW	2113 NE	1848 SE
Field Yield (g m^{-2})	940 NW 894 SW	1144 NE	1132 NE 1212 SE	1289 NE 1337 SE	490 NW	778 NE	747 SE
Evapotranspiration (mm)	535 NW 562 SW	637 NE	779 NE 701 SE	772 NE 831 SE	791 NW	909 NE	931 SW

1/ Numbers in brackets are day of year.
2/ Grain yields are reported at 14% wc (wb) for sorghum and wheat and 15.5% wc (wb) for corn.
3/ Plants were lodged.
4/ Dry matter was not harvested to leave residue for subsequent fallow research.

Table 2. Summary of the 24-h climatic variables used to evaluate evapotranspiration models for irrigated crops with full ground cover and amply supplied with water and crop characteristics during these periods at Bushland, Texas.

PARAMETER	MEAN	MAXIMUM	MINIMUM	N
Winter Wheat 1989-90, 1991-92, 1992-93 Seasons				
Tmean (°C)	14.1	21.6	2.4	84
Tmax (°C)	22.4	31.4	8.7	84
Tmin (°C)	5.6	14.4	-2.8	84
Tdew (°C)	1.1	-6.8	8.2	84
VPD (kPa)	1.20	2.24	0.42	84
2-m Wind Speed ($m\ s^{-1}$)	4.6	7.4	1.9	84
Solar Rad. ($MJ\ m^{-2}\ d^{-1}$)	23.4	29.8	11.5	84
Net Rad. ($MJ\ m^{-2}\ d^{-1}$)	13.5	20.1	7.4	84
Soil Heat Flux ($MJ\ m^{-2}\ d^{-1}$)	-0.01	1.28	-1.49	84
Crop Height (m)	0.58	1.10	0.15	84
Leaf Area Index ($m^2\ m^{-2}$)	4.67	7.20	2.95	84
Corn 1989 and 1990 Seasons				
Tmean (°C)	22.7	27.1	12.3	148
Tmax (°C)	29.6	36.4	20.6	148
Tmin (°C)	15.7	19.8	3.8	148
Tdew (°C)	12.3	17.2	3.6	148
VPD (kPa)	1.56	2.94	0.46	148
2-m Wind Speed ($m\ s^{-1}$)	3.5	6.6	1.2	148
Solar Rad. ($MJ\ m^{-2}\ d^{-1}$)	23.1	29.1	11.9	148
Net Rad. ($MJ\ m^{-2}\ d^{-1}$)	14.1	18.6	5.9	148
Soil Heat Flux ($MJ\ m^{-2}\ d^{-1}$)	-0.71	1.03	-0.71	148
Crop Height (m)	2.40	2.87	0.92	148
Leaf Area Index ($m^2\ m^{-2}$)	4.40	5.78	2.75	148
Sorghum 1988 and 1993 Seasons				
Tmean (°C)	21.2	27.6	13.2	112
Tmax (°C)	28.7	35.9	19.6	112
Tmin (°C)	13.8	20.7	3.8	112
Tdew (°C)	10.6	16.8	0.0	112
VPD (kPa)	1.52	2.59	0.41	112
2-m Wind Speed ($m\ s^{-1}$)	4.1	6.1	2.1	112
Solar Rad. ($MJ\ m^{-2}\ d^{-1}$)	22.2	28.5	13.3	112
Net Rad. ($MJ\ m^{-2}\ d^{-1}$)	13.1	19.8	7.0	112
Soil Heat Flux ($MJ\ m^{-2}\ d^{-1}$)	0.10	1.45	-0.85	112
Crop Height (m)	1.10	1.48	0.68	112
Leaf Area Index ($m^2\ m^{-2}$)	3.82	5.17	2.90	112

Table 3. Mean, maximum, and minimum daily evapotranspiration of well-watered, full-ground-cover crops (ET_l) or as estimated ET_p by several equations at Bushland, Texas. Regression coefficients are for estimated ET_p (dependent variable) versus ET_l (independent variable) for each equation.

Model	Equations	Evapotranspiration (mm d^{-1}) Mean	Maximum	Minimum	SE of Mean	ET_p/ET_l Ratio	Regression Coefficients Intercept mm d^{-1}	Slope -----	r^2 -----	$S_{y/x}$ mm d^{-1}
Winter Wheat 1989-90, 1991-92, and 1992-93 Seasons										
ET_l	-----	7.39	13.86	2.61	0.25	-----	-----	-----	-----	-----
$ET_{pm(100)}$ [1]	1, 8	8.37	16.52	3.53	0.32	1.13	ns	1.14	0.984	1.12
$ET_{pm(150)}$	1, 8	7.11	14.48	3.34	0.27	0.96	ns	0.96	0.981	1.04
$ET_{pm(135)}$	1, 8	7.42	15.03	3.13	0.28	1.01	ns	1.01	0.982	1.05
ET_{pml}	1, 9	7.68	16.40	2.43	0.33	1.03	ns	1.06	0.968	1.48
ET_{pen48}	11	6.53	10.61	3.31	0.17	0.91	1.98	0.62	0.770	0.77
ET_{fao}	12	7.83	13.29	3.97	0.23	1.08	1.92	0.80	0.782	0.96
ET_{kpen}	13	9.23	16.32	4.30	0.29	1.27	1.66	1.02	0.785	1.22
ET_{jh}	15	5.11	8.41	1.92	0.16	0.70	1.30	0.52	0.616	0.93
ET_{pt}	14	4.44	7.04	2.35	0.12	0.63	2.16	0.31	0.401	0.86
Corn 1989 and 1990 Seasons										
ET_l	-----	6.72	12.43	2.50	0.15	-----	-----	-----	-----	-----
$ET_{pm(200)}$	1, 8	7.60	12.21	3.02	0.17	1.14	1.04	0.98	0.734	1.05
$ET_{pm(250)}$	1, 8	6.74	10.79	2.68	0.15	1.01	0.90	0.87	0.734	0.94
$ET_{pm(252)}$	1, 8	6.71	10.74	2.67	0.15	1.01	0.89	0.87	0.734	0.86
ET_{pml}	1, 9	5.67	10.17	1.59	0.15	0.84	ns	0.85	0.980	0.85
ET_{pen48}	11	6.87	11.53	3.62	0.12	1.05	1.89	0.74	0.793	0.68
ET_{fao}	12	7.90	14.17	3.93	0.16	1.20	1.71	0.92	0.748	0.95
ET_{kpen}	13	8.72	15.97	4.07	0.18	1.32	1.60	1.06	0.715	1.19
ET_{jh}	15	6.90	9.82	3.48	0.12	1.05	2.19	0.71	0.764	0.71
ET_{pt}	14	5.38	7.51	2.35	0.09	0.83	2.31	0.46	0.619	0.64

[1] Subscripts for the ET_{pm} equations refer to the r_l value.

Table 3 Continued. Mean, maximum, and minimum daily evapotranspiration of well-watered, full-ground-cover crops (ET_l) or as estimated ET_p by several equations at Bushland, Texas. Regression coefficients are for estimated ET_p (dependent variable) versus ET_l (independent variable) for each equation.

		Evapotranspiration (mm d^{-1})					Regression Coefficients			
Model	Equations	Mean	Maximum	Minimum	SE of Mean	ET_p/ET_l Ratio	Intercept mm d^{-1}	Slope -----	r^2 -----	$S_{y/x}$ mm d^{-1}
Sorghum 1988 and 1993 Seasons										
ET_l	-----	5.58	10.20	2.37	0.17	-----	-----	-----	-----	-----
$ET_{pm(200)}$ 1/	1, 8	6.73	11.51	2.22	0.20	1.21	ns	1.20	0.986	0.85
$ET_{pm(250)}$	1, 8	5.96	10.31	1.94	0.18	1.07	ns	1.06	0.987	0.72
$ET_{pm(280)}$	1, 8	5.58	9.70	1.80	0.17	1.00	ns	1.00	0.988	0.66
ET_{pmi}	1, 9	4.90	9.36	1.16	0.17	0.87	ns	0.88	0.983	0.69
ET_{pen48}	11	6.75	10.66	3.11	0.15	1.25	2.19	0.82	0.835	0.64
ET_{fao}	12	7.93	12.86	3.44	0.18	1.47	2.54	0.97	0.771	0.93
ET_{kpen}	13	9.01	14.79	3.84	0.22	1.67	3.00	1.08	0.688	1.28
ET_{jh}	15	6.44	9.97	2.99	0.16	1.19	1.65	0.86	0.811	0.73
ET_{pt}	14	4.95	7.68	2.43	0.12	0.92	1.55	0.61	0.699	0.71

1/Subscripts for the ET_{pm} models refer to the r_l value.

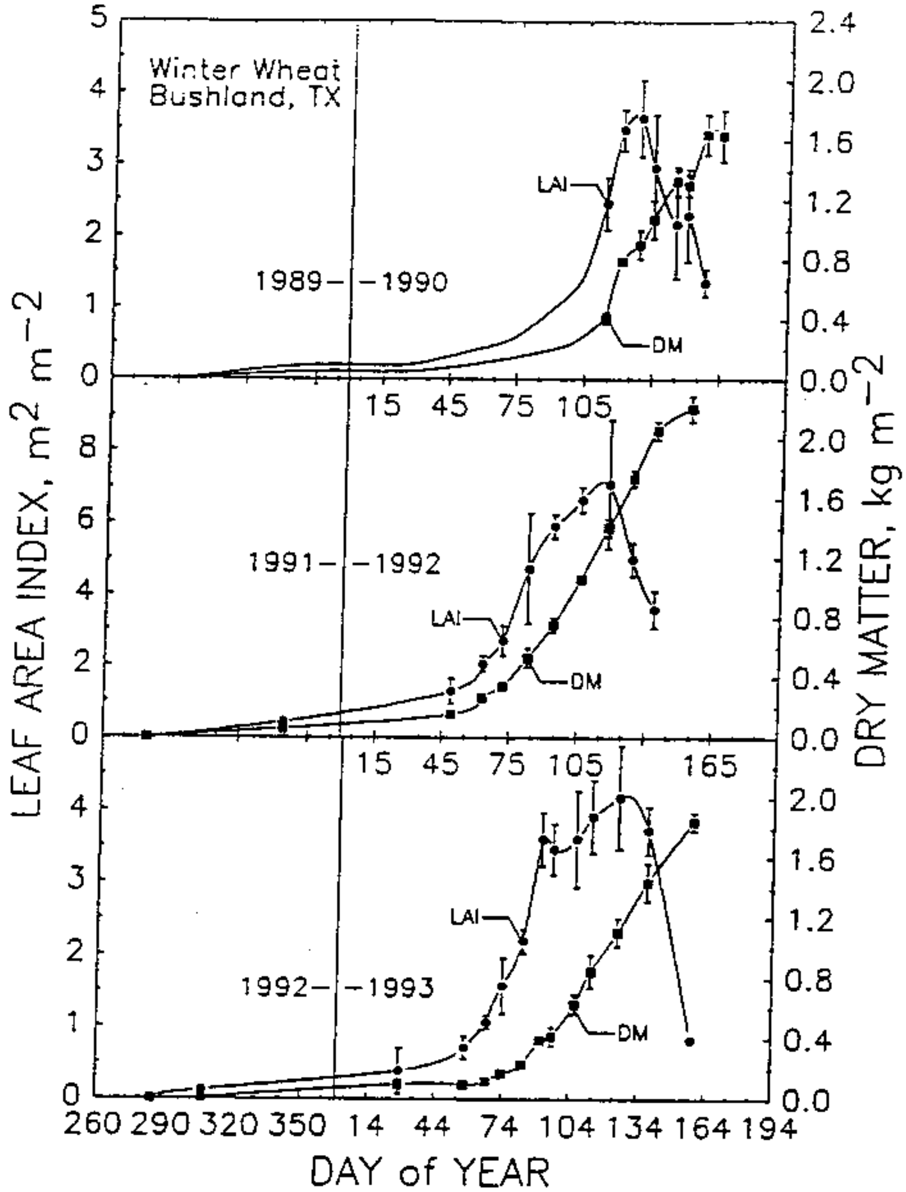

Figure 1. Leaf area index and dry matter development for irrigated winter wheat at Bushland, TX, for the 1989-90, 1991-92, and 1992-93 growing seasons.

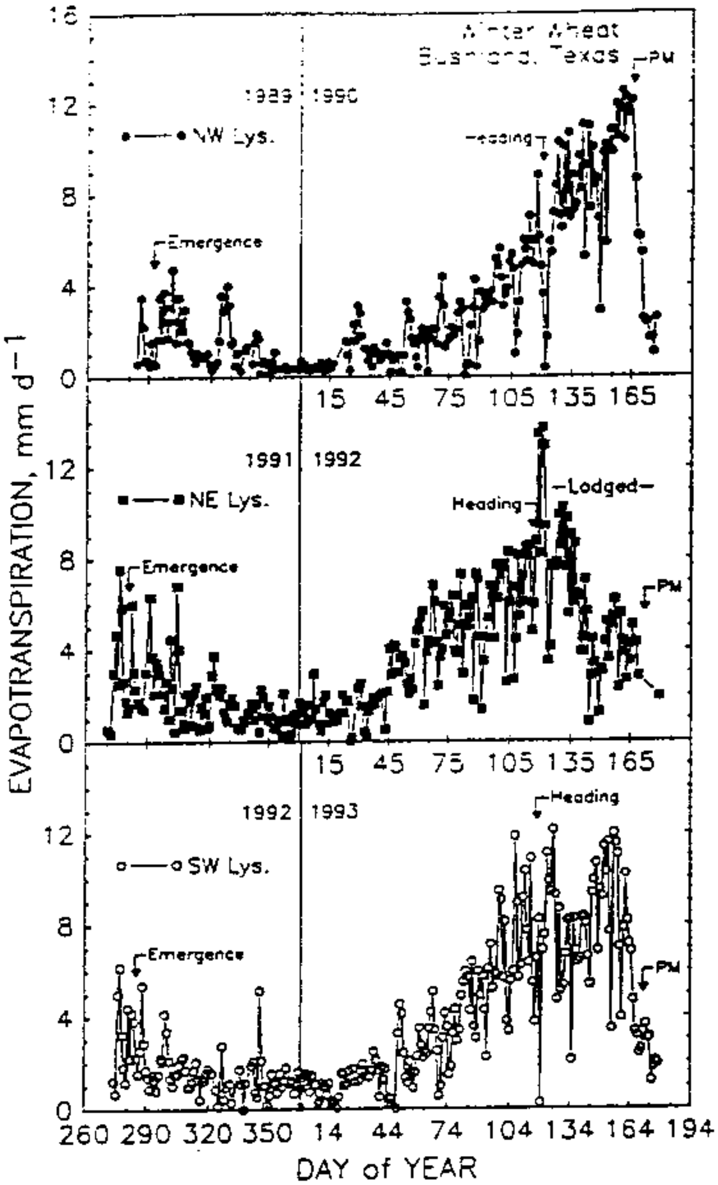

Figure 2. Daily evapotranspiration of irrigated winter wheat at Bushland, TX, for the 1989-90, 1991-92, and 1992-93 growing seasons from planting to harvest.

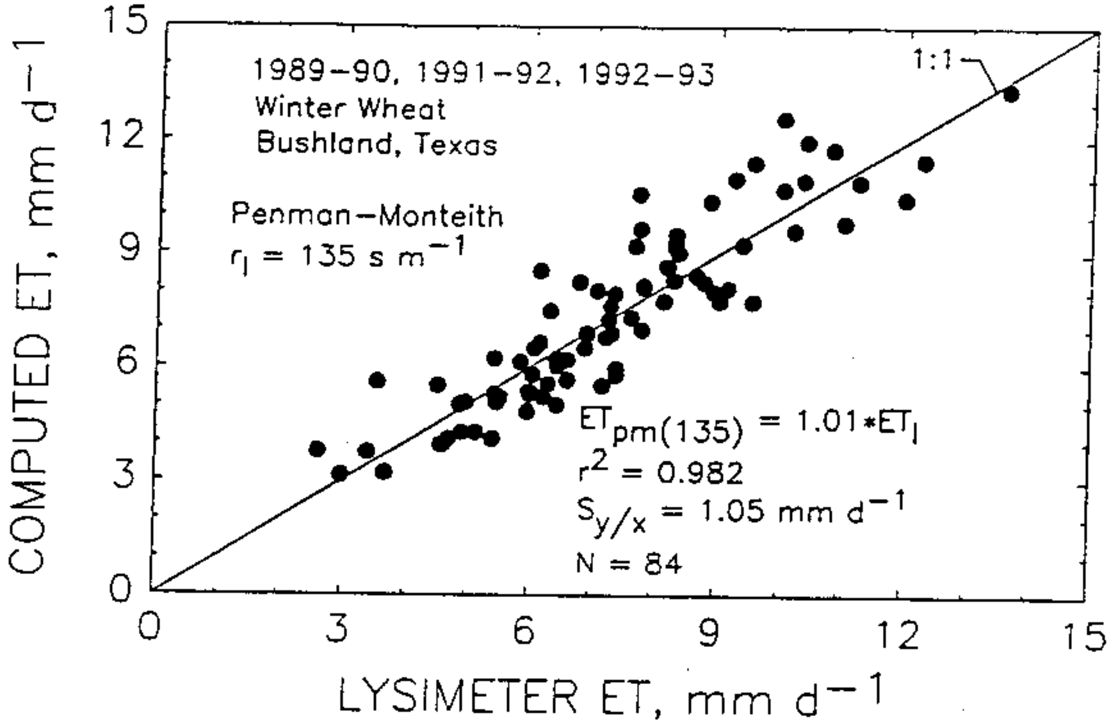

Figure 3. Maximum daily evapotranspiration of irrigated winter wheat at Bushland, TX, during the 1989-90, 1991-92, and 1992-93 growing seasons for days with full-ground cover compared with computed ET by the Penman-Monteith equation with r_l = 135 s m^{-1}.

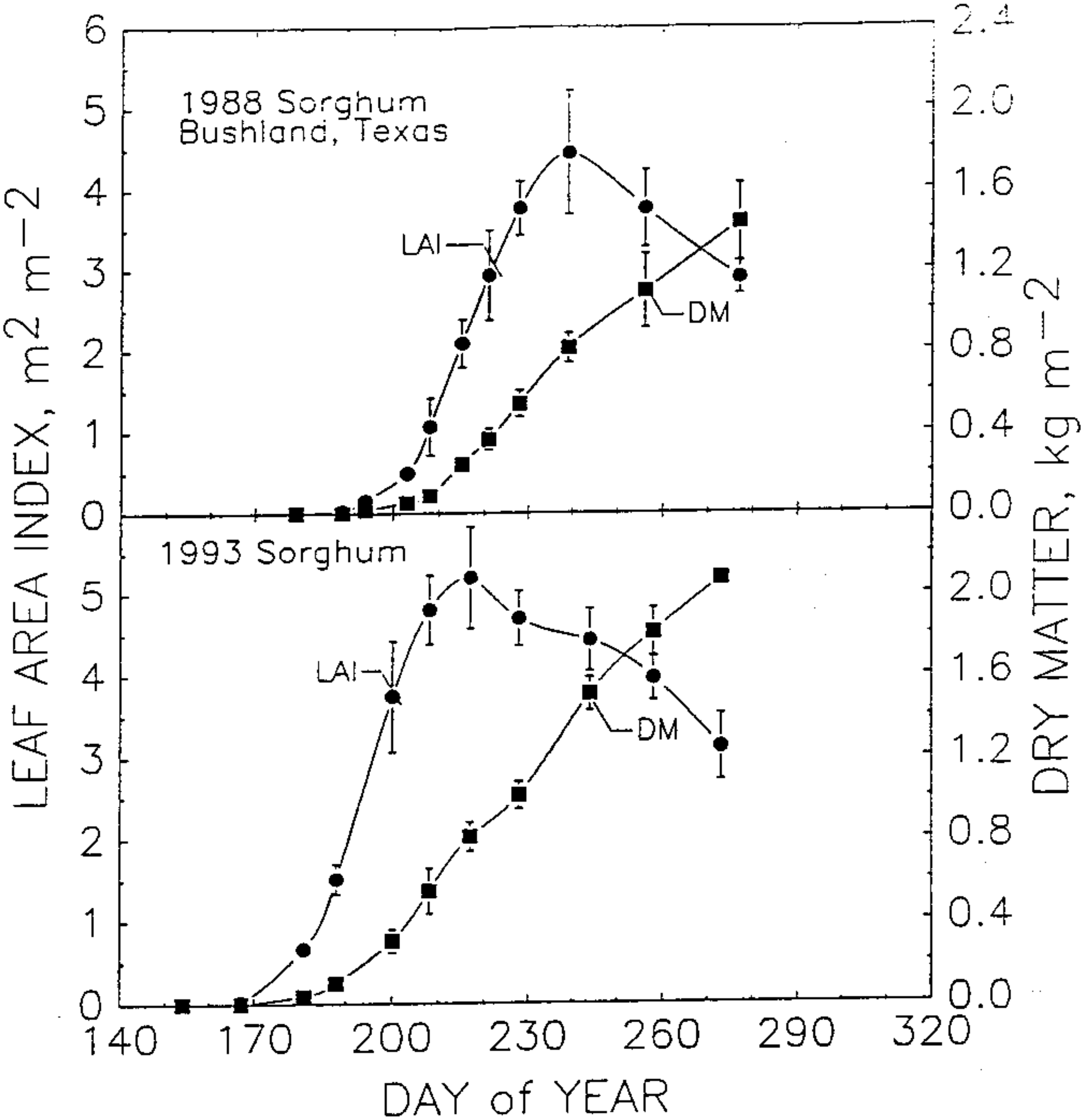

Figure 4. Leaf area index and dry matter development for irrigated sorghum at Bushland, TX, for the 1988 and 1993 growing seasons.

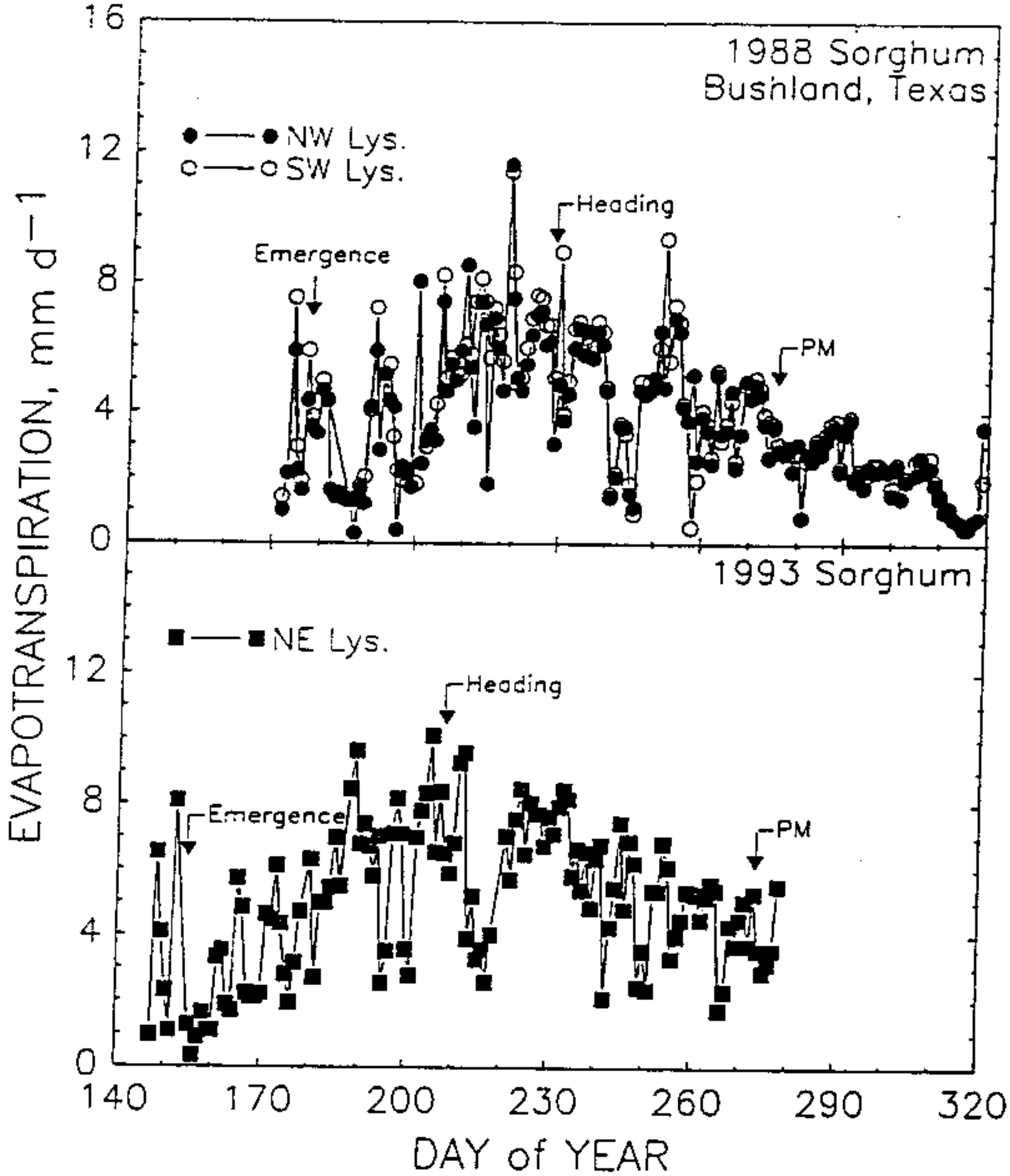

Figure 5. Daily evapotranspiration of irrigated sorghum at Bushland, TX, during the 1988 and 1993 growing seasons from planting to harvest.

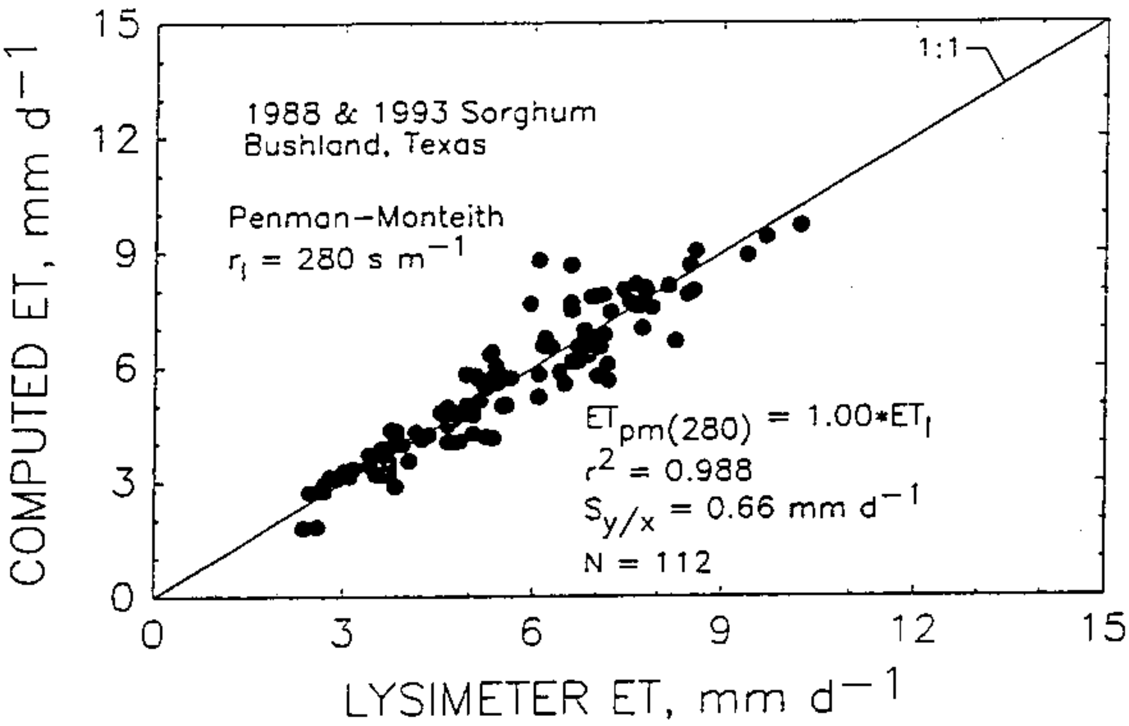

Figure 6. Maximum daily evapotranspiration of irrigated sorghum at Bushland, TX, during the 1988 and 1993 growing seasons for days with full-ground cover compared with computed ET by the Penman-Monteith equation with r_l = 280 s m^{-1}.

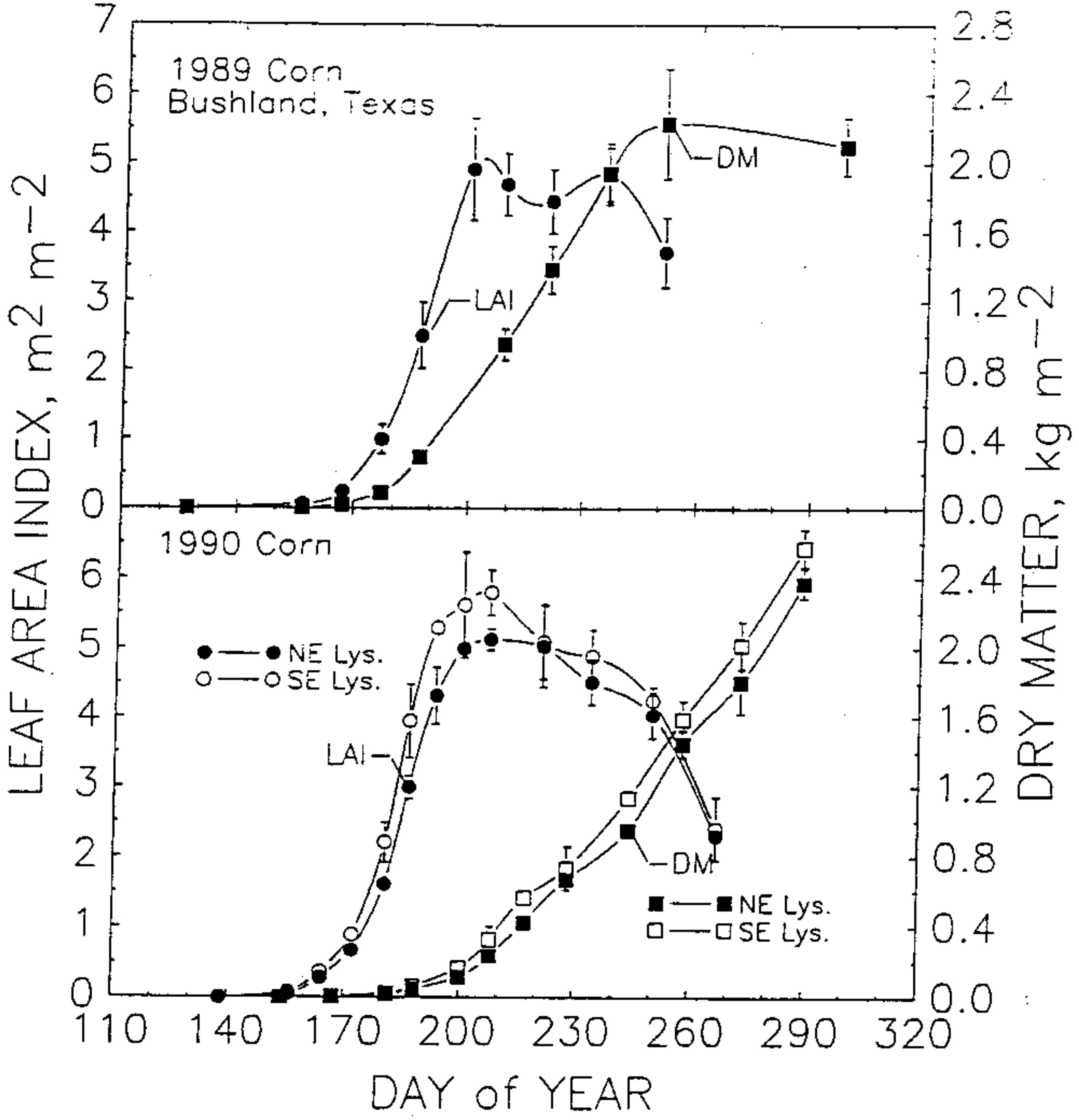

Figure 7. Leaf area index and dry matter development for irrigated corn at Bushland, TX, for the 1989 and 1990 growing seasons.

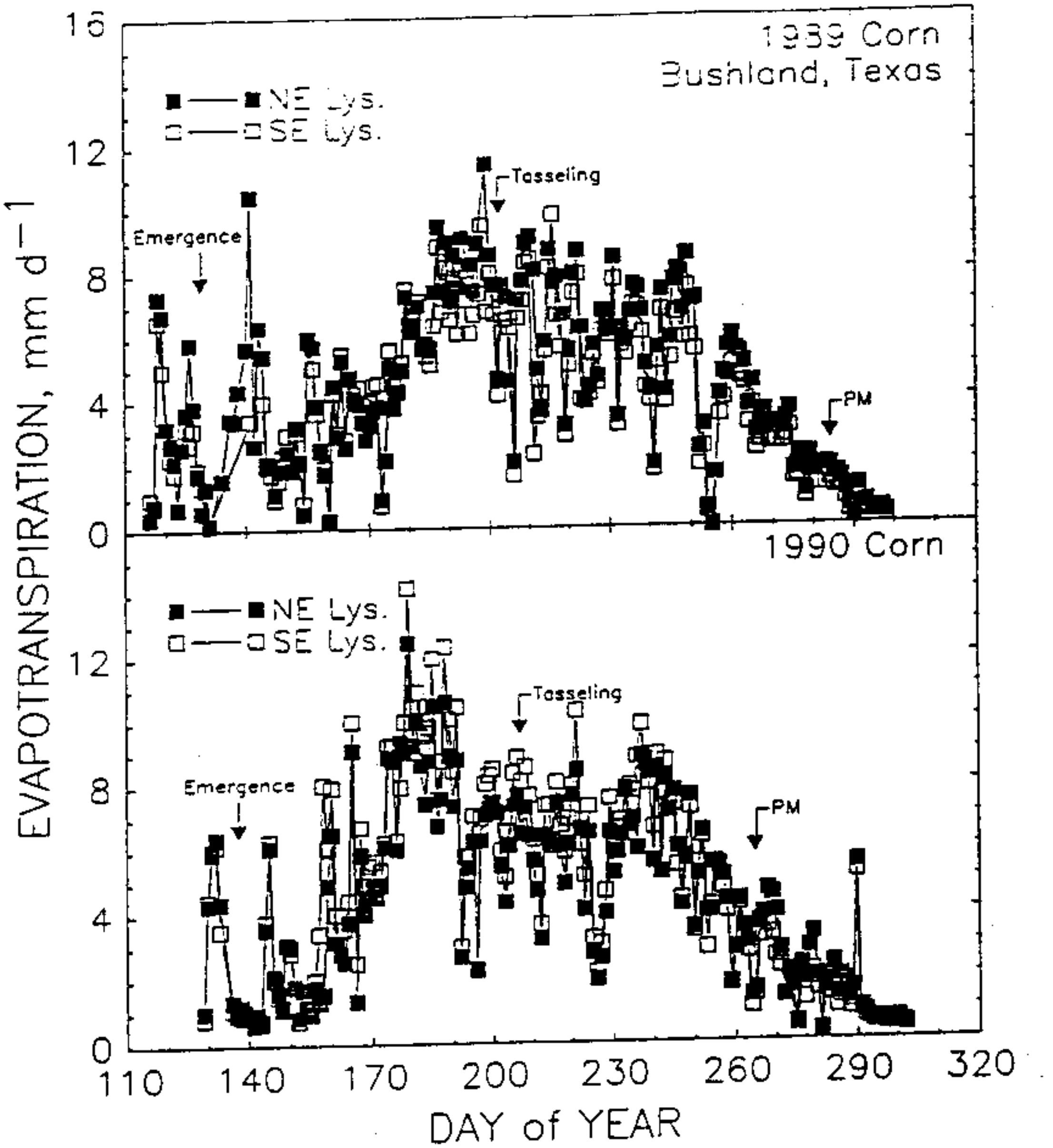

Figure 8. Daily evapotranspiration of irrigated corn at Bushland, TX, during the 1989 and 1990 growing seasons from planting to harvest.

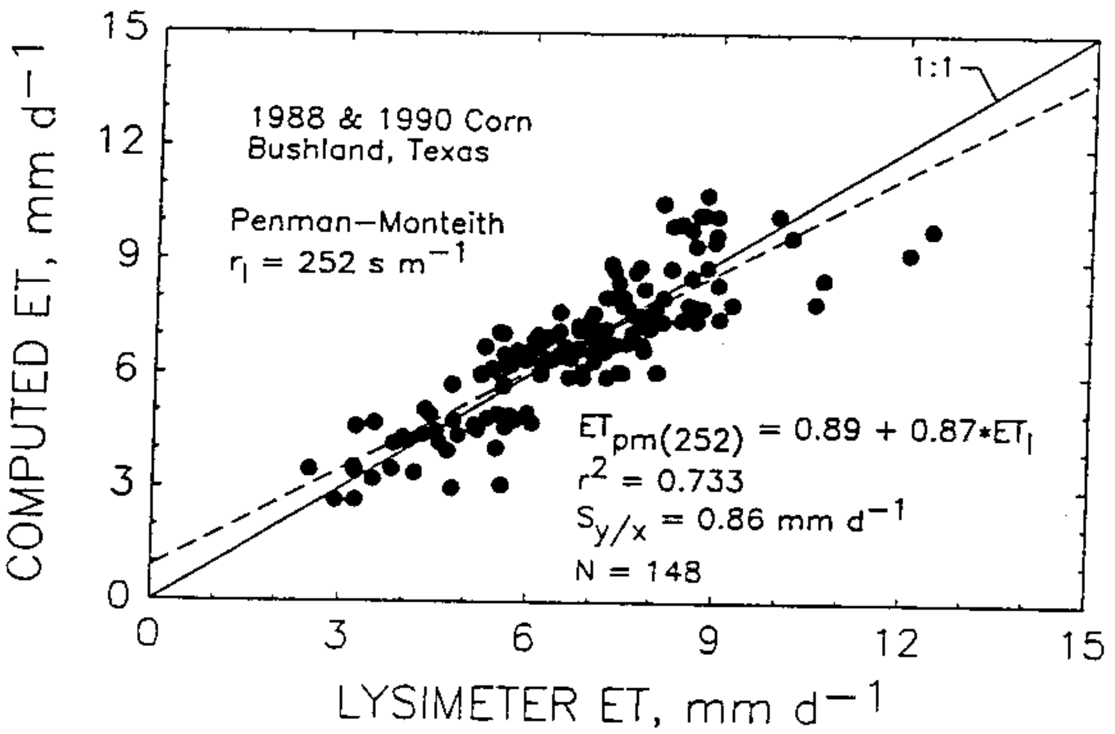

Figure 9. Maximum daily evapotranspiration of irrigated corn at Bushland, TX, during the 1989 and 1990 growing seasons for days with full-ground cover compared with computed ET by the Penman-Monteith equation with $r_l = 252$ s m^{-1}.